UNCLASSIFIED

AD 414563

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION, ALEXANDRIA, VIRGINIA

UNCLASSIFIED

ARL-63-670

6 = 4 - 5

A MODIFICATION OF THE FUJITA METHOD FOR TIROS PHOTOGRAPH RECTIFICATION

JOHN F. CRONIN

ALLIED RESEARCH ASSOCIATES, INC.

VIRGINIA ROAD   CONCORD, MASSACHUSETTS

CONTRACT No. AF 19(628)-320

AND

LEONARD W. ABREU

W.E. HOWELL ASSOCIATES, INC.

LAURENCE G. HANSCOM FIELD   BEDFORD, MASSACHUSETTS

CONTRACT No. AF 19(628)-306

A MODIFICATION OF THE FUJITA METHOD FOR TIROS PHOTOGRAPH RECTIFICATION

JOHN F. CRONIN

ALLIED RESEARCH ASSOCIATES, INC.
VIRGINIA ROAD   CONCORD, MASSACHUSETTS
CONTRACT No. AF19(628)-320

AND

LEONARD W. ABREU

W.E. HOWELL ASSOCIATES, INC.
LAURENCE G. HANSCOM FIELD   BEDFORD, MASSACHUSETTS
CONTRACT No. AF19(628)-306

ABSTRACT

A Manual technique is described that enables the research meteorologist and others to portray with maximum accuracy a latitude-longitude net on a satellite photograph of the earth and its cloud masses. Unlike other techniques a rectification may be obtained for any orbit; heretofore, orbits without horizons could not be rectified graphically.

TABLE OF CONTENTS

1. Introduction

A recent report by the National Aeronautics and Space Administration
(Ref. 1) (1962) states that the problem of determining the exact geographic
location of the individual TIROS pictures still remains. Admittedly this
was the final report on TIROS I, but if one were to search the meteoro-
logical journals issued to date (November 1962) one would not find any
refutation of this statement or any exposition of the several techniques
available for the rectification of any of the TIROS series of meteorological
satellites. Perhaps what is more regrettable is the publication in the
literature of certain articles purporting to interpret features observed in
TIROS photos whose authors have erred to some extent in their analyses
solely because they have not located the exact geographic position of the
events described.

Rather than to detail the several techniques that are in use today this
paper will describe the one particular method, the so-called Fujita method,
which, together with modifications by the authors was found to be of consi-
derable value in mesometeorological research at the Satellite Meteorology
Branch of the Air Force Cambridge Research Laboratories. Dr. Tetsuya
Fujita of the Department of Geophysical Science of the University of Chicago
first made known his method in a report (Ref. 2) published in November 1961.
It is a technique designed specifically for use with the TIROS satellites but
could be readily adapted for use with other picture-taking satellites or
certain high-altitude aircraft. The Fujita method deserves greater recog-
nition, and it is hoped that this article will aid in circulating the method
more widely among the meteorological community.

It is the purpose of this report to provide only a working manual of
the method. The complete theory of the technique was recently issued,
January 1963, by Fujita (Ref. 3). Terms used in this paper are identical
to those of Fujita's latter paper and are among those adopted by the
Conference on Glossary of Satellite Meteorology in September 1962.

2. Orbital and Camera Characteristics

TIROS is a spin-stabilized satellite with its spin axis fixed in space and its cameras approximately parallel to the spin axis. Tables I - 1 and I - 2 summarize the pertinent orbital and camera data.

TIROS	Apogee (Kilometers)	Perigee (Kilometers)	Eccentricity	Inclination to Equator (Degrees)
I	753	690	.0044	48.40
II	742	608	.0095	48.58
III	820	736	.0058	47.90
IV	844	710	.0093	48.30
V	970	591	.0266	58.10
VI	704	692	.0008	58.32

Table I - 1. Orbital Elements

It is obvious from the eccentricities that the TIROS orbits are very nearly circular, much more so, for instance, than a polar cross section through the Earth. The eccentricity of the Earth, the planet, that is -- not its orbit -- is 0.082; whereas that of TIROS V is only 0.0265. Yet TIROS V has a difference of 381 kilometers between apogee and perigee and the Earth a difference of only 21 kilometers between its equatorial and polar radii. For the curious and those to whom an explanation is not readily apparent, the solution is given in the Appendix. One may also use the elementary formulae of the Appendix to compute the eccentricity, given perigee and apogee, of any satellite.

It might be of interest to point out that at TIROS altitudes, altitudes in the exosphere, i. e., above 550 km., the dominant perturbation of an orbit is that due to the flattening of the earth. The force on a satellite of typical size at these altitudes is about 10^8 dynes and the variation in this force due to the earth's flattening is about 2×10^5 dynes. Atmospheric drag at 500 km. is less than 10 dynes. The force due to irregularities of the gravitational field is only 200 dynes.

2

TIROS	Launch Date	Date of Last Usable Photographs	Field of View (Degrees) Cam. 1	Cam. 2	Focal Length (Mm) Cam. 1	Cam. 2	Optical Axis Deviation Cam. 1	Cam. 2
I	1Apr 60	17 June60	12.7	104	40.0	5.3	0.73°	0.45°
II	23Nov60	5 May 61	12.7	104	40.0	5.3	0.52°	0.47°
III	12July61	20 Oct 61	104	104	5.3	5.3	0.37°	0.53°
IV	8 Feb 62	10 June62	104	76	5.0	5.7	0.53°	0.34°
V	19June62	Transmitting	104	76	5.0	5.7	0.62°	0.64°
VI	18Sept62	Transmitting	104	76	5.0	5.7	0.53°	0.38°

Table I - 2. Camera Characteristics

The angles listed under "Field of View" in Table I - 2 are those most commonly quoted and are the designed full angle dimensions between fiducial corners. The actual half angle measurements derived from polar test target images are given in the Appendix. Use of the 12.7° angle camera of TIROS I and II is not anticipated in future meteorological satellites, except possibly in orbits of high eccentricity, nor has any method of rectification, manual or computer dr·wn, been devised for such a narrow angle camera.

The "Optical Axis Deviations" of Table I - 2 illustrate the near-parallel alignment of the optical axes with the spin axes. None of the 12 cameras deviated as much as a degree.

Other terms and data, rather frequently used, are listed in Table I - 3.

Descriptive Designation	Camera Field of View Angle (degrees)	Area (Square Miles)	TV Resolution
Wide Angle	104	600,000*	1 1/2 miles
Medium Angle	76	230,000*	1 mile
Narrow Angle	12.7	6,000*	1000 feet

Table I - 3. Some Image Parameters

* Area viewed when satellite is 725 kilometers above the earth and the spin axis is perpendicular to the earth's surface.
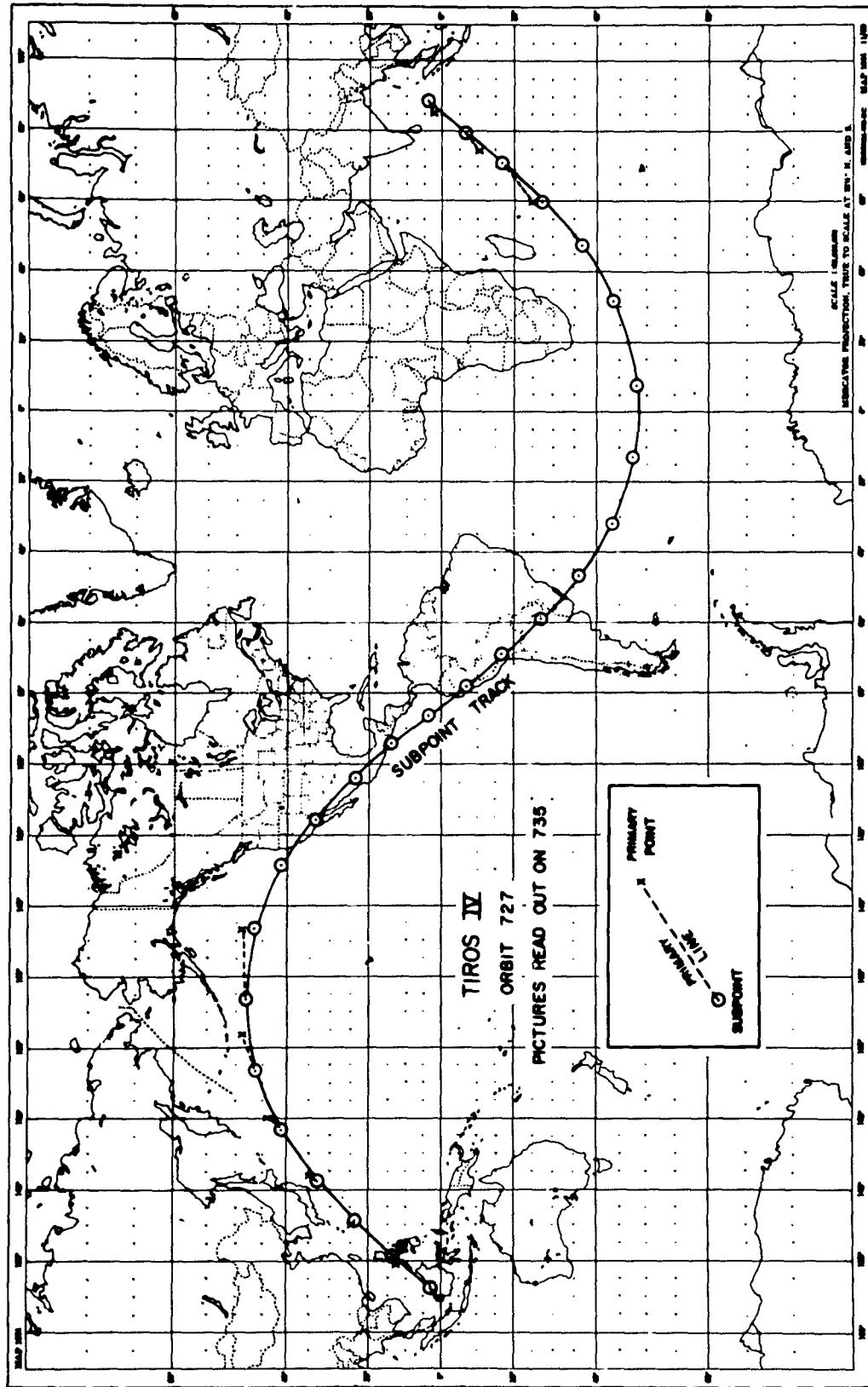
Figure 1. A typical orbit of TIROS IV. This particular orbit is used throughout the report.

3. Geometry

The term "rectification" has rather broad connotation in photogrammetry but is most often used to denote either the reduction or enlargement of photographs, transforming a tilted photograph to a vertical photograph or the technique of fitting a geographic grid to a photograph. Rectification as Fujita uses the term is this last definition.

A TIROS satellite will describe two tracks across the earth's surface which are of immediate significance. One is the track of the subpoints, the TSP (terrestrial subpoint) track and the other is the track of the primary points, the TPM (terrestrial primary point) track (Fig. 1). The subpoint is a point on earth directly below the vehicle. The primary point on earth is the point where the spin axis intercepts the earth's surface. At any particular moment of time, i. e. , when a photograph is taken, the satellite, the TSP, its corresponding TPM and the center of the earth will all lie in one plane. The intersection of this plane with the earth's surface is termed the primary line (see Fig. 7). It is the precise location of primary lines that is most important in the rectification of satellite photos.

4. Required Data

The source of all basic data, except the time of picture-taking, is the Definitive AT Map (formerly referred to as the "World Map") issued for each TIROS by the National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland. This "map" is actually a computer print-out tabulation of orbital data which includes among other things, the particular data necessary for this modified Fujita technique, i. e. , the minute by minute height, subpoint, principal point and nadir angle of the satellite. Picture sequence time is obtained from the Documentation Unit, Meteorological Satellite Activities, U. S. Weather Bureau, Washington 25, D. C. The film is obtainable from the National Weather Records Center, U. S. Weather Bureau, Arcade Building, Asheville, N. C.

5. Required Map and Grids

The following material is needed for the Fujita method of rectification and can be obtained from the Meteorological Satellite Laboratory, U. S. Weather Bureau, Washington, D. C. Each of these is defined and illustrated in succeeding pages.

1a. Oblique Equidistant Cylindrical Projection, Inclination 48.4°. (Tiros I-IV)

1b. Oblique Equidistant Cylindrical Projection, Inclination 58.3°. (Tiros V, VI)

2. Overlay to the Oblique Equidistant Cylindrical Projection.

3. Set of Tilt Grids, 0 to 60 degrees.

4. Set of Height Grids, 600 to 960 kms.

5. Distortion-Free Fiducial Grid; one for each camera of each TIROS.

6. Table of Symbols

OEC projection	oblique equidistant cylindrical projection
TSP	terrestrial subsatellite point
TPM	terrestrial primary point
TSA	terrestrial spin axis point
η	nadir angle
FSA	fixed-earth spin axis point
ISP	image subsatellite point
IPM	image primary point
e	orbital eccentricity

PART II - THE METHOD

Normally during an orbit each of the two cameras is scheduled to take
32 pictures. If the pictures are to be stored on tape and read out later they
are programmed at 30-second intervals, but if the pictures are to be trans-
mitted directly to the read-out site as they are taken then the interval is 10 or 30
seconds between frames. Not infrequently, for one reason or another, photos
are taken at irregular intervals of time. Using the Fujita technique, one can
determine the difference between the programmed and actual exposure times
of each frame.

Fujita states (Ref. 2) that in order to perform a rectification at least
1 or 2 frames of an orbit should have good earth horizons. In our variation
of his technique earth horizons are not necessary.

The base map devised by Fujita is described as an Oblique Equidistant
Cylindrical Projection (Fig. 2), hereafter termed the OEC Projection.
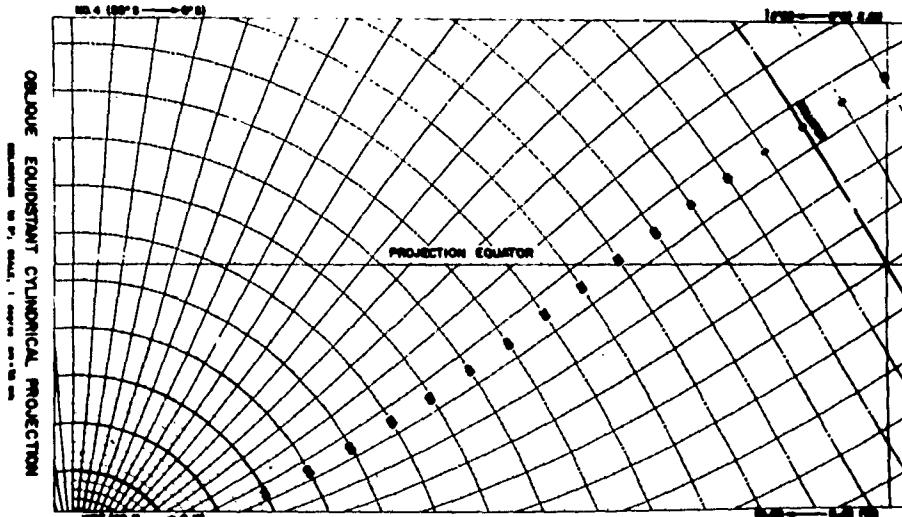

Figure 2. A base map for the Fujita method

This OEC Projection, like the oblique Mercator projection (Fig. 3), is
a cylindrical projection in which the cylinder is tangent to the earth at a
great circle other than the equator - as it is in the direct Mercator, and
other than a meridian - as it is in the transverse Mercator.

7

Direct **Transverse** **Oblique**
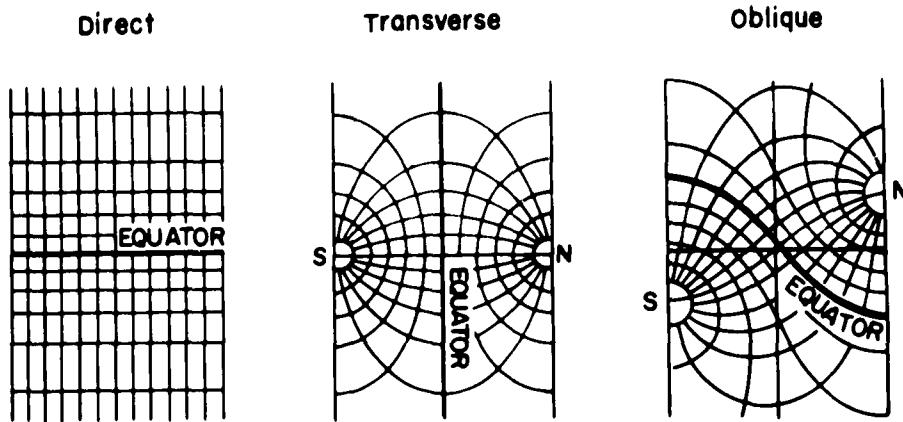
Figure 3. The three types of Mercator projections. The OEC Projection is similar to the oblique Mercator.

The great circle of tangency on the OEC Projection represents the intersection of the plane of inclination of the satellite's orbit with the earth's surface. Distances along this great circle, which is defined as the projection equator, and along any perpendicular to the same equator are actual earth distances. The oblique Mercator shows true scale only along the great circle of tangency.

The 48.4° chart is to be used with TIROS I - IV and the 58.3° chart with TIROS V and VI.

1. Construction of Tracks on OEC Projection

Step A: Draw Terrestrial Subpoint (TSP) Track

Obtain from the NASA Definitive AT Map the terrestrial subpoints (TSP) of each frame; these are listed on the print-out sheets as "Satellite Coordinates" (See Table II-1). This line of points, which becomes the TSP track, is plotted on the OEC Projection so that the TSPs of the frames to be rectified fall as close as possible to the projection equator. Occasionally two OEC projections may be needed side by side.

Step B: Construct Terrestrial Primary Point (TPM) Track

From the same source plot the terrestrial primary points (TPM) of all frames. NASA lists these points as "Picture Center Coordinates" (see Table II-1). This line of points is the TPM track.

Table II-1   NASA Attitude Map for Orbit 727, TIROS IV.

Frame	Time[1]			Satellite Coordinates[2]			Picture Center Coordinates[4]		Nadir Angle
	Day	Hr	Min	Lat	Long	Hgt[3]	Lat	Long	
32	31	04	01	18.7	125.7	743	18.4	124.3	11
30	31	04	02	21.3	128.2	747	21.3	127.1	8
28	31	04	03	23.8	130.7	751	24.1	129.9	6
26	31	04	04	26.3	133.4	756	26.9	133.0	5
24	31	04	05	28.7	136.2	760	29.6	136.1	7
22	31	04	06	31.0	139.1	764	32.2	139.5	9
20	31	04	07	33.3	142.2	769	34.7	143.1	13
18	31	04	08	35.4	145.5	773	37.1	146.9	16
16	31	04	09	37.4	148.9	778	39.4	150.9	19
14	31	04	10	39.3	152.5	783	41.5	155.3	23
12	31	04	11	41.1	156.3	787	43.5	160.1	26
10	31	04	12	42.7	160.4	791	45.2	165.1	30

1. Frame time given by Weather Bureau; not shown in NASA "Map"
2. Fujita symbol, TSP.
3. Height in kilometers.
4. Fujita symbol, TPM.

During TIROS I, II and III the determination of "Picture Center Coordinates" was not as accurate as it might have been. Although the system improved with IV it is recommended that the following procedure be used to verify or improve the plot of TPM points. This can be done with the aid of satellite nadir angles and the "Height Grids".

The satellite nadir angles for each frame are obtained by interpolating between the minute by minute nadir angles published in the NASA Attitude Map.

The height grids (Fig. 4) are polar charts constructed at 10 km intervals and designed to be used with the OEC projection. The slightly curved radii of the height grid are azimuth lines along which great circle distances may be measured. The concentric circles of the height grid represent degrees of nadir angle.

HEIGHT GRID, H = 760 km,

HEIGHT GRID, H = 760km, S = 36 7°
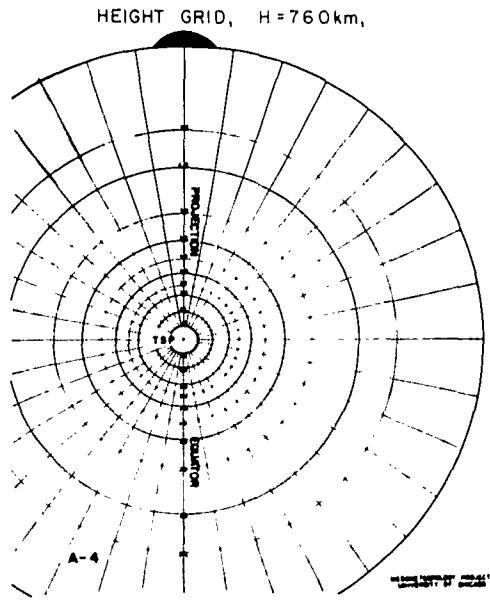
Figure 4.   One of the Set of Height   Figure 5.   Revision of TPM
            Grids
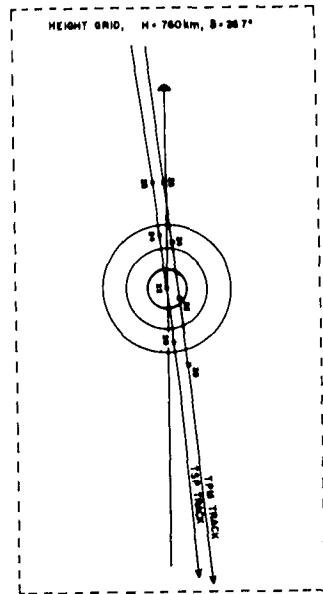
The center of the appropriate height grid for a particular frame is
overlaid by a TSP of the OEC projection with the projection equator of each
initially parallel.   The OEC projection is rotated slightly until the nearest
azimuth of the height grid passes through the TSP and its corresponding
TPM.   The distance from the center of the height grid to the TPM should
equal the nadir angle of the frame (Fig. 5).   If it does not, the TPM should
be shifted along the TPM track to the intersection of the nadir angle circle
with the TPM track.

In those instances where the TPMs are obviously in considerable
error it is suggested that one of the methods devised by Fujita (Ref. 3) be
used to construct the TPM track.

Step C: Construct Terrestrial Spin Axis (TSA) Track

The OEC Overlay (Fig. 6) is introduced with this step and, like the
height grid, was constructed for use with the OEC projection.   Azimuth or
primary lines are great circles through the origin along which great circle
distances may be measured.   Degrees of nadir angle may also be measured
from the origin.

NADIR ANGLE (η)
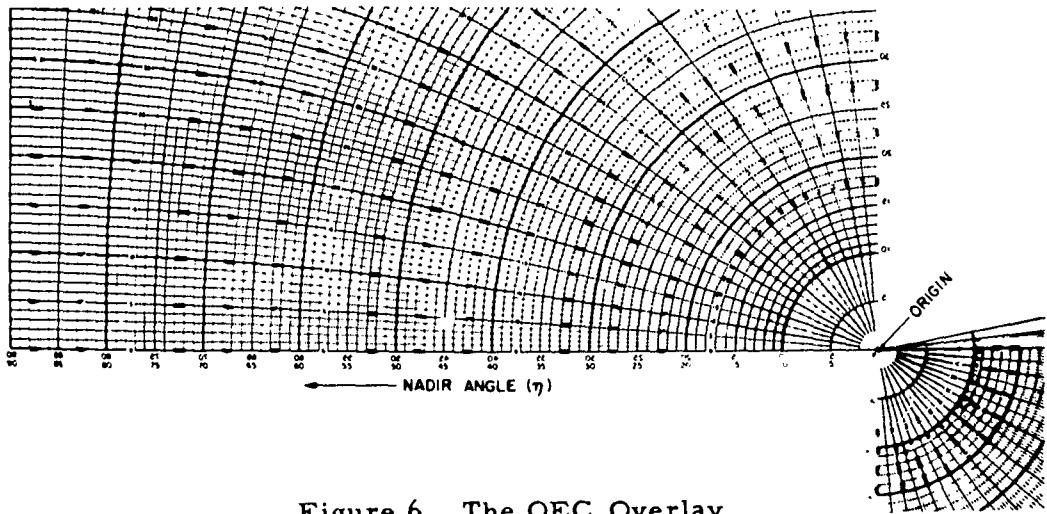
Figure 6. The OEC Overlay

Since the geometry of the TSA track is rather difficult to grasp we will not state at this point why we need the track but only define and describe it. Once we know what it is, why will be obvious. For the sake of clarity we will, (1) define TSA, (2) describe its geometry for a fixed earth, i. e. an imaginary earth whose rotation has stopped, (3) portray its path on the rotating earth and (4) describe the construction of the TSA track . Figures 7 and 8 illustrate definition and description.
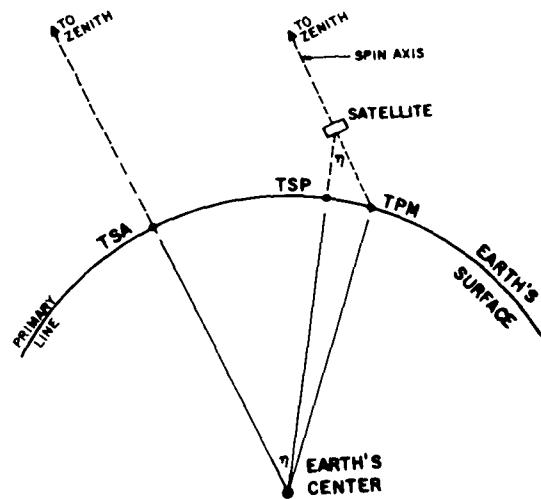
Figure 7. Geometry of Earth, Satellite and Celestial Sphere

11

1) Definition: The TSA is that one point on the earth's surface where the spin axis would be perpendicular to the earth. Actually the spin axis is very rarely, if ever, perpendicular to the earth. However, it is possible to locate this point by translation. That is the goal of this step, to locate the point where the spin axis would be perpendicular to earth and then to construct the path of this point, the TSA track, as the earth rotates.

It might be well to point out that the spin axis referred to here is not the satellite spin axis but the apparent spin axis of the lens and the photograph, termed the nodal spin axis by Fujita.

2) For a fixed earth: The TSA would remain at the same point during the entire orbit. Nutations of satellite and earth can be overlooked.

Note that as the satellite moves along its orbit the spin axis intersects at a series of points termed the TPM points and that the angle formed by the TPM, the satellite and the TSP is the nadir angle (See Fig. 7). Note that the angle formed by TSA, the earth's center and TSP is also equal to the nadir angle.

3) For a rotating earth:

| (a) | (b) | (c) |
| FIXED EARTH | ROTATING EARTH AT TIME X | ROTATING EARTH AT TIME Y |
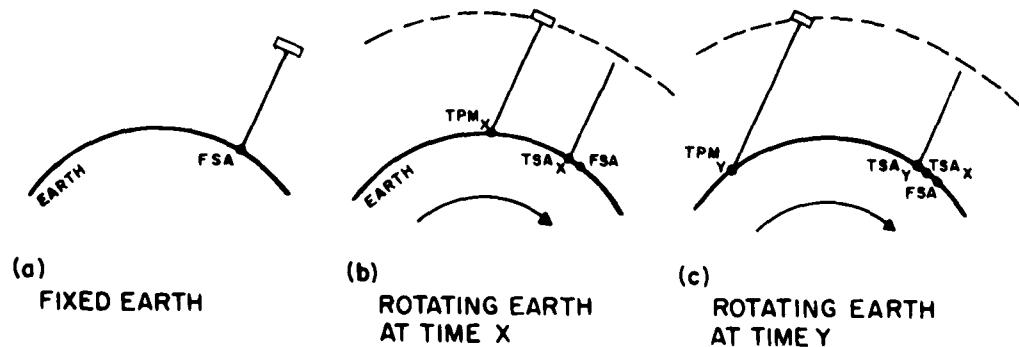
Figure 8. The relationship of the rotating earth and the "perpendicular axis"

Let us translate the satellite and its spin axis to that point where the axis is perpendicular to earth. Let us fix the trace of the axis in space while the earth rotates under it and the satellite continues on its way. Again for the sake of clarity

let us term this fixed axis the "perpendicular axis" and change the designation of TSA to FSA for the fixed earth location (Fig. 8a).

With the satellite in motion and the earth turning, the "perpendicular axis" at time $\underline{X}$ intersects the earth at TSA_x, at time $\underline{Y}$ at point TSA_y, etc. thus tracing a course of TSA points (Figures 8b and 8c). Note that the displacement of TSA is considerably less than that of TPM; the rotational velocity of the earth is considerably less than the orbital velocity of the satellite.

Drop a line down from the satellite to the earth's center in Figures 8b and 8c and note that TSP (the point of intersection with the earth) is displaced more than TSA and less than TPM. This will be illustrated again in a later step.

4) Construction: The TSA for several alternate frames are found by first centering, in turn, alternate TSPs of the OEC projection on the origin of the OEC overlay with the TPM always in the smaller quadrant of the OEC overlay (Fig. 9). Then with the projection equator of the OEC overlay parallel to the projection equator of the OEC projection follow the azimuth, which is also a primary line, from the TPM through its TSP until it intersects the appropriate nadir angle arc in the larger quadrant of the OEC overlay. The point of intersection is the TSA for this particular frame (Fig. 9). Repeat for several alternate frames.


Frame	Minutes Prior To Frame "Zero"	Degrees West Of Frame "Zero"
20	10	2 1/2
22	11	2 3/4
24	12	3
26	13	3 1/4

NOTE: Frame zero is to the right of this portion of the orbit.
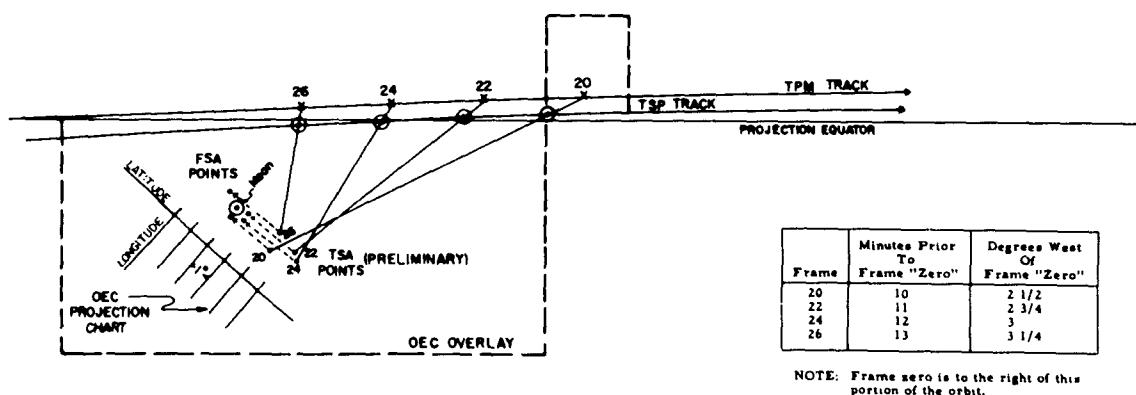
Figure 9. Determination of Mean Position of Fixed-Earth Spin Axis (FSA) Points

13

Let us now assume that a picture was taken at that point where the spin axis is perpendicular to earth (FSA of Figure 8) and let us term this picture "frame zero". Fujita designates this fictitious frame to be that immediately following the last frame. Actually any point in the orbit could be termed frame zero, for if the earth did not rotate all TSAs would fall at the point of frame zero. We shall follow Fujita's example.

For a taped orbit, as is orbit 727 of this report, where the interval between pictures is 30 seconds and the frames are always transmitted to earth in the reverse order to that in which they were taken, frame zero is 30 seconds prior to frame number one (see Fig. 10). For a direct orbit where the interval between pictures is 10 or 30 seconds, frame zero would be 10 or 30 seconds after the last frame or highest numbered frame.

To locate the FSA of taped orbit 727 we shall locate the FSA or each frame, although theoretically they should all fall on the same point. Each TSA is moved westward along its latitude (to subtract the earth's eastward rotation) $1/4^\circ$ of longitude per minute of time prior to the time of frame zero. Thus in Figure 9 the TSA of frame 20, which occurred 10 minutes prior to frame zero, is shifted $2\ 1/2^\circ$ west; frame 26 which was 13 minutes prior to frame zero is moved $3\ 1/4^\circ$ west. Normally, because of operational error, these FSA points will show some scatter so that one must chose a mean simply by estimating the center of the scatter. When this is done we have located the FSA of frame zero. The scattered FSAs should be within one degree of radius from the FSA of frame zero.

To sum up, we have now located by translation that point where the spin axis of this orbit would be perpendicular to earth, the FSA of the "perpendicular axis" of Figure 8a. We have designated this point to be the FSA of an imaginary frame zero.

Recalling that the FSA of frame zero is also its TSA (Figure 8a and accompanying text) and that frame zero is to be immediately after the last picture -- the last frame of this taped orbit is frame one -- we can now determine TSA of all frames by moving eastward (Figure 10) from the FSA of frame zero and along its latitude, $1/4^\circ$ of longitude per minute of time. Frame 2 is 1 minute of time or $1/4^\circ$ east of frame 0, frame 4 is 2 minutes or $1/2^\circ$ east, etc. The TSA so constructed is then the eastward displacement of the "perpendicular axis" caused by the earth's rotation.

14
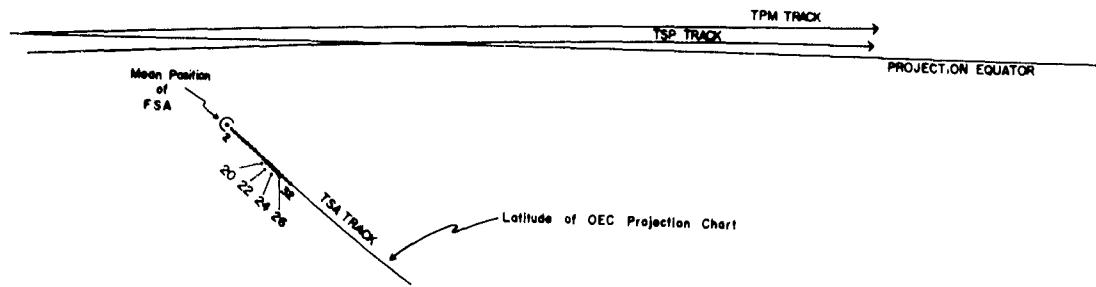
Figure 10.   Construction of Terrestrial Spin Axis (TSA) Track

Step D: Draw Primary Lines on OEC Projection
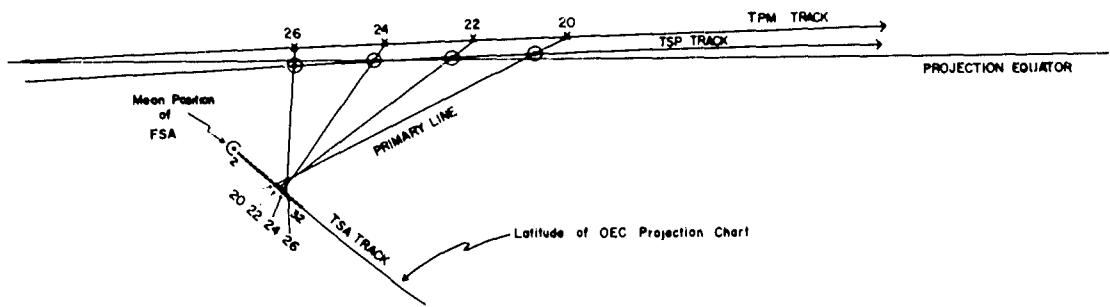
Figure 11.   Construction of Primary Lines

The primary line is a great circle passing through the TSA, TSP and TPM of a frame (See Figure 7).   Having obtained the TSPs and TPMs from the NASA AT Map and the TSAs in Step C we find the primary line of a frame by connecting the three points (Figure 11) as demonstrated in succeeding paragraphs.   If the earth did not rotate all primary lines would meet at a common TSA.

If the orbit contains an identifiable landmark, this step is performed only for the frame or frames with a landmark.   The primary lines of the frames would then be considered preliminary.   However, if in the picture

sequence one cannot recognize any geographical features, this step is repeated for each frame, and all of Section 3 is omitted.
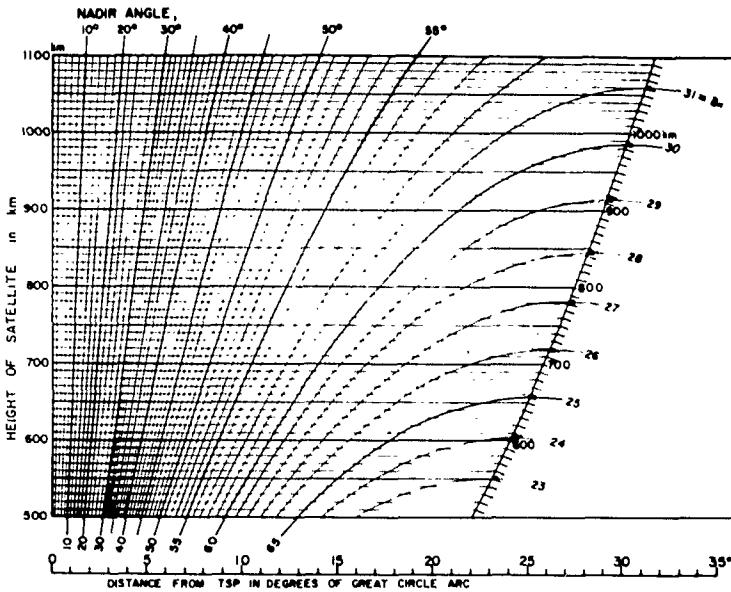
Figure 12. Nadir Angle Chart

While we are drawing the primary lines we will simultaneously verify and possibly revise the TPMs for a second time. It should be reiterated that of the various data used in this method the "Picture Center Coordinates" (TPMs), particularly of TIROS I, II and III, and the frame times are least reliable.

On Figure 12 locate the intersection of the nadir angle and the height of frame. Drop a perpendicular from this intersection down to the scale labelled "Distance from TSP in degrees of Great Circle Arc" and record this distance. Repeat for each frame.

With the OEC projection and its overlay again oriented as in Figure 9 -- TSP on the origin, projection equators parallel and TSAs in the larger quadrant of the overlay -- extend the azimuth passing through the TSP and its corresponding TSA from the TSP into the smaller quadrant until it intercepts the distance determined by Figure 12. This is the primary line of the particular frame. Repeat for all frames. Each line should terminate, of course, at the TPM previously plotted. If not, then a revised TPM track is drawn connecting these terminations; the terminations are the revised TPMs.

16

2. Preparation of Photos and Associated Grids

Step E: Plot Image Primary Points on Photos

The distortion-free fiducial grid (Fig. 13) which is introduced with this step is a grid that depicts the image as it would appear on an undistorted image plane. Fujita has constructed a grid of a standard size for each camera of each satellite. They are made from the polar target photo obtained through the complete camera and TV system before the vehicle is launched. This grid eliminates the lens and initial electronic distortion inherent in the camera system. The IPM on the distortion-free fiducial grid is depicted by a small "x" near the center fiducial cross.
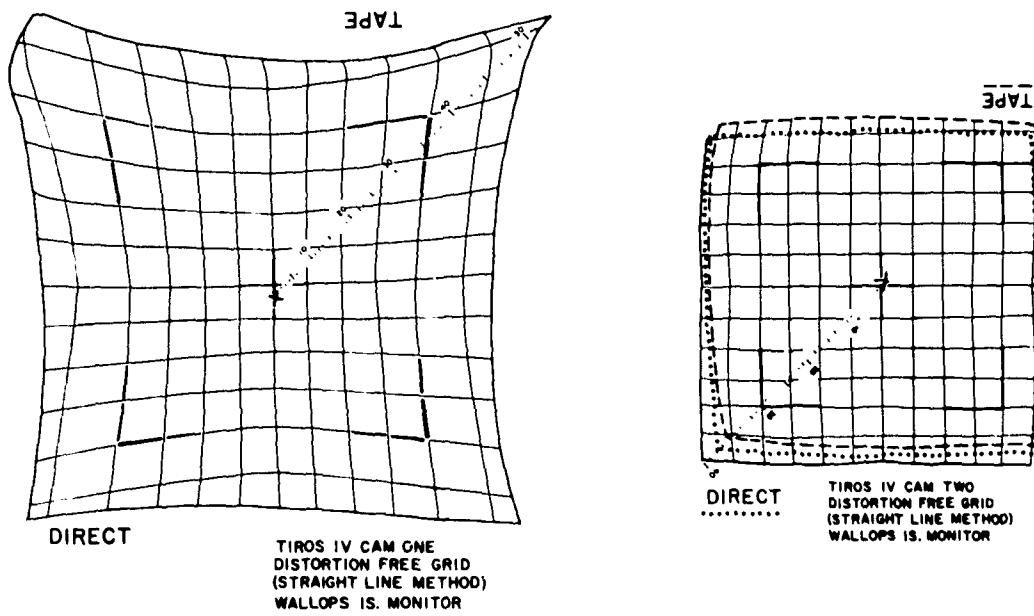
Figure 13. Distortion-Free Fiducial Grids of Each Camera of TIROS IV

Obtain a series of photos, one of each frame or every other frame. With the use of the distortion-free fiducial grid transcribe image primary points from one photo to the next (Fig. 14). Clouds or landmarks are a reference in the transcription. The words "tape" and "direct" will assist one in orienting the grid (Fig. 13). For example in orbit 727 of this report the word "tape" would be placed at the bottom or label end of the photo.

17
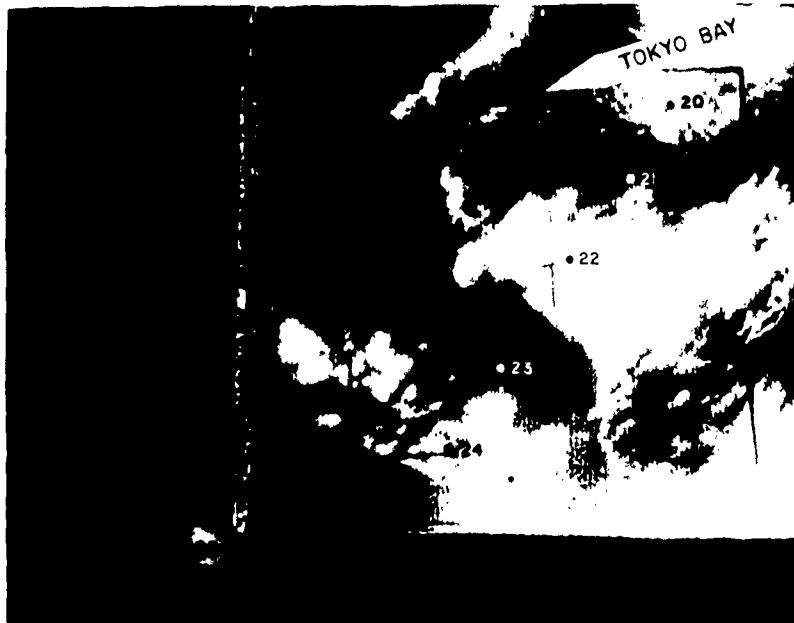
Figure 14. Plot of Primary Points on Frame 22, Orbit 727, TIROS IV
(Fig. 14 is oriented approximately north-south)

Step F: Construct Fiducial Grid

The transmission of the photo from the satellite to the ground station
often results in appreciable distortion varying from day to day. Use of the
fiducial grid in the transfer of points from any size picture to the distortion-
free fiducial grid as used in Step G will eliminate this type of distortion.
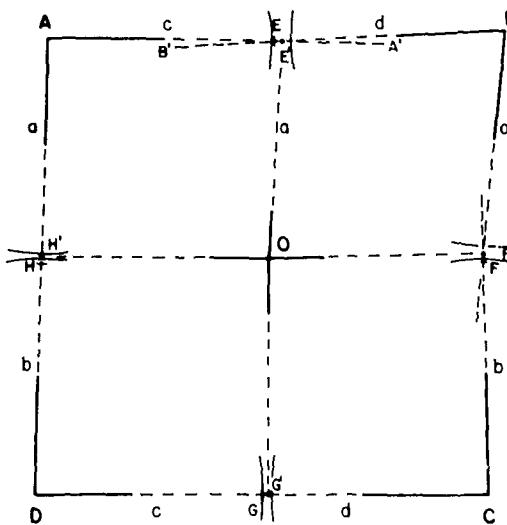
Figure 15a. Construction of Fiducial
Grid
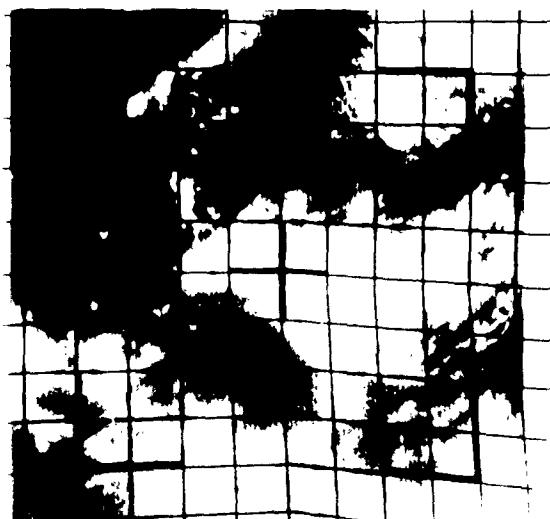
Figure 15b. Frame 22 with its
Fiducial Grid

18

Trace corner fiducials and center cross from a photo on to a transparency (Fig. 15a) and extend corner fiducials until they intersect. Find midpoint of a line (not shown) between A and B and draw a short perpendicular (at E). The acute angles formed by AA' and BB' are bisected, and the intersection of the bisector with the perpendicular is designated as E. The distance from E to O is represented by the arc a, swung from corners A and B.

Repeat for side BC. Locate midpoint, construct perpendicular (at F), bisect acute angles (vertical in this case) and intercept perpendicular at F. The distance from O to F is represented by the arc d, swung from corners B and C.

Sides AD and DC are each a single line so that one need only locate the midpoints H and G. The distance from O to H is represented by the arc c and that from O to G by the arc b. Between each arc pair locate the midpoints E', F', G' and H'. If the sides are two converging lines the midpoint should be on the bisector of the acute angles. Quadrisect each side of each quadrilateral OE'BF', etc. and construct net as shown in Figure 15b.

Step G: Construct Image Primary (IPM) Track on Distortion-Free Fiducial Grid

To construct the IPM track one would first place a fiducial grid as constructed in Step F over a photo and trace the principal points from the photo on to the fiducial grid. Then transcribe from the latter to the distortion-free fiducial grid. A curve through these points is the IPM track (see Fig. 18).

Step H: Construction of Primary Lines on Distortion-Free Fiducial Grid

The tilt grid (Fig. 16) is an image plane consisting of the isolines of nadir angle. The isolines of nadir angle are a group of ellipses which are the intersection of the image plane and a group of cones of various nadir angle.
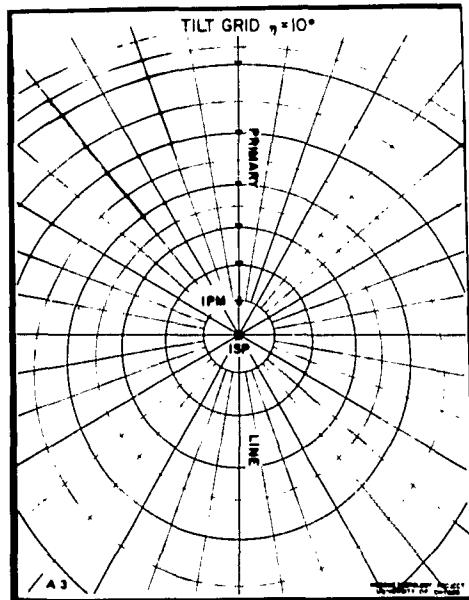
Figure 16. One of the Set of Tilt Grids

To illustrate this step frame 22 of orbit 727 was chosen. On Table II-1 we see that the nadir angle of frame 22 is 9° and the height, 764 km. The center (TSP) of the 760 km. height grid is placed beneath the TSP plot of frame 22 on the OEC projection so that originally the projection equators are parallel. Then rotate the OEC projection until the preliminary primary line of frame 22 on the OEC projection coincides with the nearest azimuth of the height grid (Fig. 17).

20
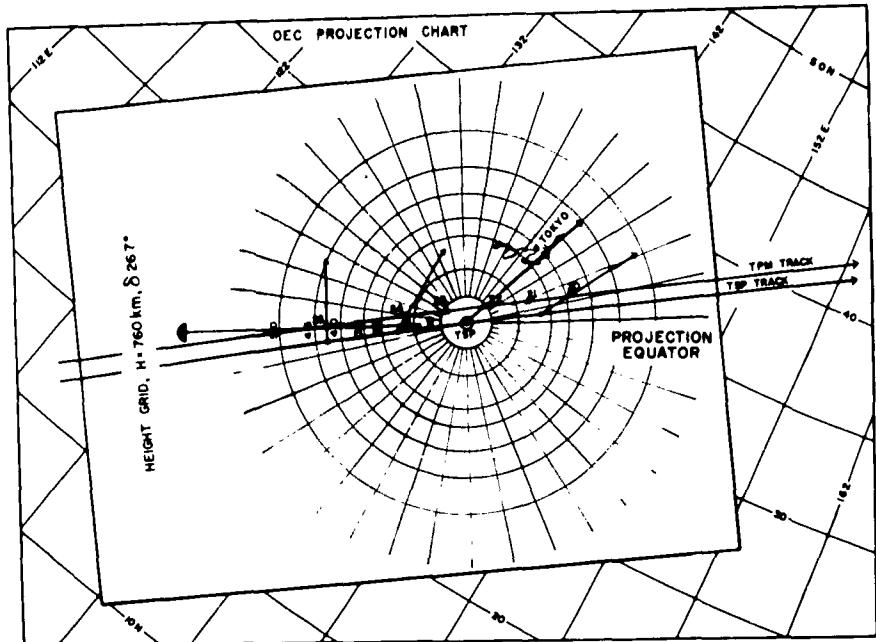
Figure 17. Location on Base Map of Primary Line of Frame 22,
Orbit 727, TIROS IV

Placing the distortion-free fiducial grid of frame 22 on the 10° tilt grid
so that the IPM of frame 22 is also on the primary line of the tilt grid, shift
the distortion-free fiducial grid until the IPM of frame 22 is 9° of nadir angle
from the ISP of the tilt grid (Fig. 18).   Now rotate the distortion-free
fiducial grid either right or left until angle formed by IPM track and the
primary line of the tilt grid (Fig. 18) equals that formed by the TPM track
and the primary line of frame 22 on the OEC projection (Fig. 17). The rela-
tionship of the primary line to the primary track in Figure 18 should be identical
to that in Figure 17.
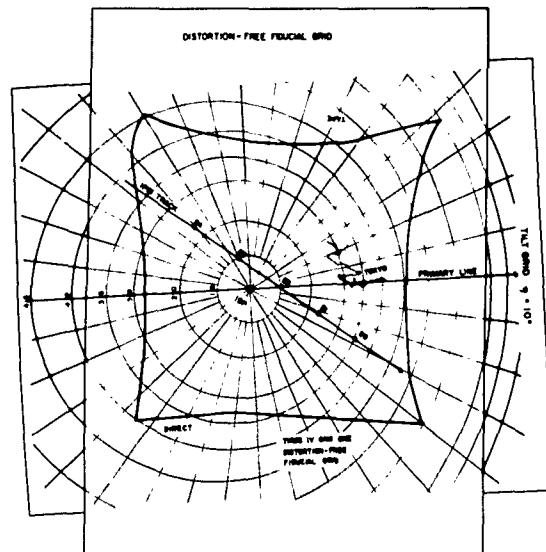
Figure 18. Construction of Primary Line on the Distortion-Free Fiducial
Grid of Frame 22

21

Recalling that the vertical line of the tilt grid (Fig. 16) is a primary line, trace this primary line on to the distortion-free fiducial grid.

This step should be performed for all frames of an orbit if the orbit does not have any landmarks. If there is a landmark within an orbit this is done only for those frames with landmarks and all grids would remain in same position for Step J.

3. Preliminary Rectification of Orbits with Geography

If an identifiable landmark appears during the picture sequence it is possible to obtain more precise TSPs, TPMs and primary lines. One can also obtain exact picture-taking times and thus correct the occasional error in the time of direct mode pictures and the more appreciable error that frequently occurs in the times of tape-mode pictures.

Step I: Plot Landmark on OEC Projection and the Distortion-
Free Fiducial Grid of Frame with Landmark

On the OEC projection, latitude and longitude determine the location of the landmark. For the distortion-free fiducial grid, the landmark is traced first on to the fiducial grid from the photo and then transferred to the distortion-free fiducial grid.

Step J: Construction of Final Primary Line for Frame with
Geography

Note location of landmark with respect to primary lines in both Figures 17 and 18. If landmark does not match we then shift grids in the following manner until best fit is attained.

The distortion-free fiducial grid is rotated and the OEC projection is moved right or left along the TSP track until the relationship of landmark to primary line is as alike as possible in both figures. This will produce an exact TSP and TPM on the OEC projection for this particular frame. Now we obtain final primary line on the distortion-free fiducial grid by tracing the primary line of the tilt grid on the distortion-free fiducial grid.

Step K: Construction of Final Primary Lines on OEC Projection

Having located the exact TSP and TPM on the OEC projection of frame with landmark in Step J the more precise TSPs and TPMs of all other frames are located by moving each of these preliminary TSPs and TPMs in a like direction and amount. Final primary lines can now be drawn on the OEC

22

projection by centering the TSP of the OEC overlay below each TSP of the OEC
projection, with the projection equator of the OEC projection parallel to the
projection equator of the overlay, and tracing the azimuth through corresponding
TSAs and TPMs.

> Step L: Construction of Final Primary Lines on Distortion-
> Free Fiducial Grids.

Repeat Step H - third and fourth paragraphs - for all frames, using
revised TSPs and TPMs.

4. Construction of Latitude-Longitude Grids on Photos

> Step M: Transcription from OEC Projection to Distortion-
> Free Fiducial Grid

Again, as in Step H, Figures 17 and 18, place center of appropriate
height grid on a revised TSP of the OEC projection with projection equators
closely parallel and with an azimuth of the height grid coincident with the
primary line. At the same time, place the distortion-free fiducial grid of the
same frame over the appropriate tilt grid with the IPM and primary line of
the distortion-free fiducial grid coincident with the IPM and primary line of
the tilt grid. We are now ready to transcribe latitude-longitude intersections
from the OEC projection to the distortion-free fiducial grid (Fig. 19).
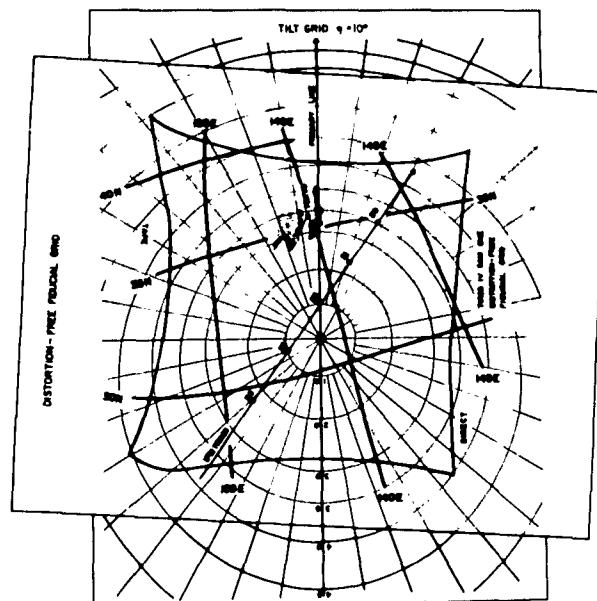
Figure 19. The Transcription of the Latitude-Longitude Net From
the OEC Projection to the Distortion-Free Fiducial Grid

23

<u>Step N</u>: Transcription from Distortion-Free Fiducial Grid
to Photos

The final step is the transfer of latitude-longitude intersections from
the distortion-free fiducial grids to each fiducial grid. The geographic grid
can now be drawn on each photo (Fig. 20).
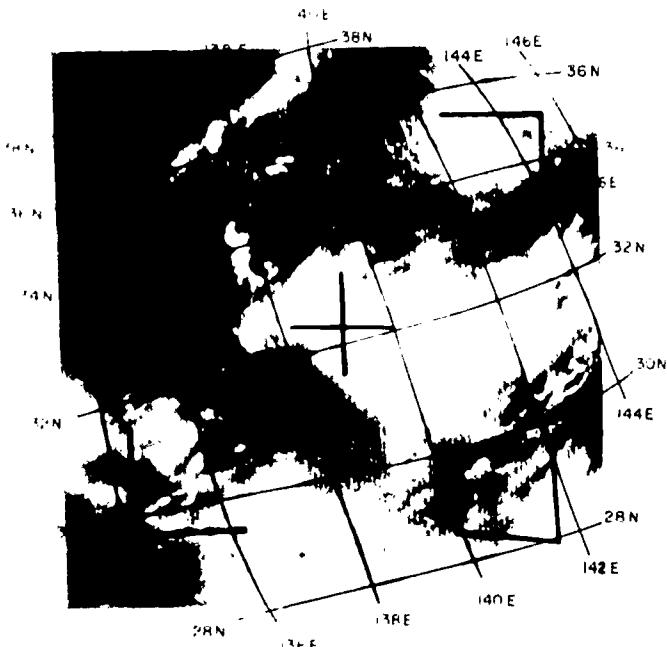
Figure 20.   The Geographic Grid Superimposed on Frame 22

5. Discussion of Results

ARACON Laboratories and the Satellite Meteorology Branch of the Air
Force Cambridge Research Laboratories has attained a consistent accuracy
of 1/5 to 1/10 of a degree using this modified Fujita method for TIROS photo-
graph rectification. It is a modification that, among other things, has
quickened the rectification procedure by using the primary points and nadir angles
published by NASA. In the original paper this information is obtained by
several additional steps which require an earth horizon on at least one or two
photographs of an orbit. The technique outlined in this paper does not require
horizons and, though abbreviated, will achieve the same degree of accuracy
as Fujita's more extended method.

The ease with which one can acquire the basic data and the rapidity,
accuracy and simplicity of this technique should encourage a greater use of
TIROS photography, particularly among those who do not have access to
computer grid-drawing facilities.

24

6. References

1. National Aeronautics and Space Administration, 1962: FINAL REPORT ON THE TIROS I METEOROLOGICAL SATELLITE SYSTEM. NASA Technical Report R-131 Goddard Space Flight Center, Greenbelt, Maryland.

2. Fujita, T., 1961: OUTLINE OF A TECHNIQUE FOR PRECISE RECTIFICATION OF SATELLITE CLOUD PHOTOGRAPHS. Research Paper No. 3, Technical Report to the U.S. Weather Bureau, Contract Cwb 10047 (MSL), Department of Geophysical Science, The University of Chicago, Chicago, Illinois.

3. Fujita, T., 1963: A TECHNIQUE FOR PRECISE ANALYSIS FOR SATELLITE DATA; VOLUME I - PHOTOGRAMMETRY. Meteorological Satellite Laboratory Report No. 14, Weather Bureau, U.S. Department of Commerce, Washington, D.C.

7. Appendix

a) Camera Test Data

"Radial Angle" of the following table is the angle formed by the principal point of the polar test target, the lens, and a circle of the polar target; it is often described as a lens half angle. In the following table the data in the "Radial Angle" columns are the test target measurements of the angular intercepts listed in the "Circle" columns.
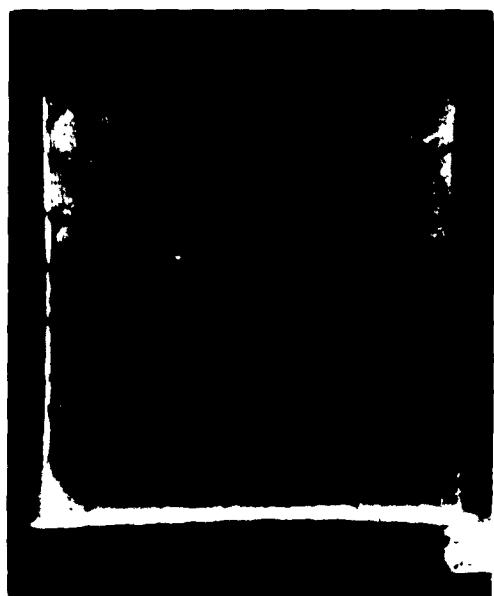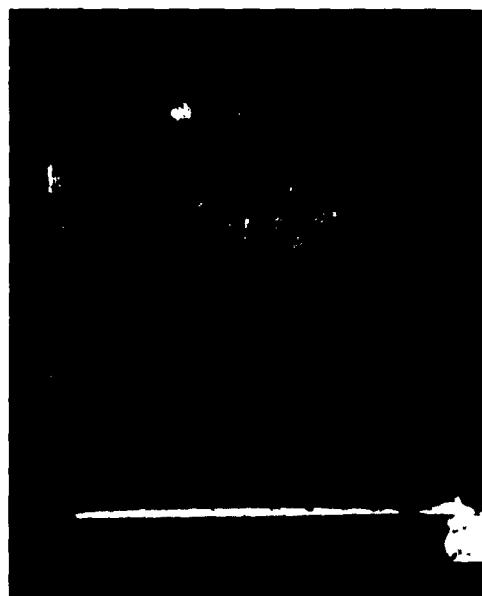
Figure 1.   Direct Mode Test Pattern for Camera No. 1, TIROS V

Figure 2.   Direct Mode Test Pattern for Camera No. 2, TIROS V

	Camera 1		Camera 2	
	Circle	Radial Angle	Circle	Radial Angle
TIROS I	1°	1.00°	3°	2.68°
	2	2.00	6	5.67
	3	3.00	10	8.98
	4	3.98	15	13.52
	4.5	4.48	20	18.08
	5	4.98	25	22.70
			30	27.38
			35	32.13
TIROS II	2	2	10	9.83
	4	4	20	19.31
	6	6	30	28.90
			40	38.63
			45	43.58
TIROS III	10	9.50	10	9.62
	20	18.83	20	19.07
	30	28.33	30	28.63
	35	33.15	35	33.48
	40	38.02	40	38.38
	45	42.97	45	43.33
	50	47.98	50	48.35
TIROS IV	10	9.18	10	9.08
	20	18.23	20	18.05
	25	22.82	25	22.58
	30	27.50	30	27.23
	35	32.24	35	31.95
	40	37.05		
	45	41.97		
	50	46.98		
TIROS V	10	10.52	10	10.25
	20	20.73	20	20.23
	25	25.83	25	25.22
	30	30.88	30	30.22
	35	35.95	35	35.20
	40	40.96		

b) <u>Determination of Satellite Orbital Eccentricity, Given Apogee and Perigee</u>

Let; a = semi-major axis of orbit

A = Apogee, the distance from earth to most distant point of orbit.

P = Perigee, the distance from earth to nearest point of orbit.

F_E = Distance from perigee to "center" of earth. The "center" of the earth is one of the foci of a satellite orbit.

R_E = 6371.23 km, the mean radius of the earth.

Find;

(I) Length of semi-major axis: a

(II) Distance from perigee to one focus, the "center" of earth: F_E

(III) Distance from center of orbit to "center" of earth: $a - F_E$

(IV) Eccentricity of orbit: $e = \dfrac{a - F_E}{a}$

Ex. <u>TIROS V,</u>   apogee = 971 km

perigee = 590 km

$$a = 1/2 (A + P + 2 R_E)$$

$$= 1/2 (971 + 590 + 12,742.46)$$

$$= 7151.73 \text{ km}$$

$$F_E = P + R_E$$

$$= 590 + 6371.23$$

$$= 6961.23 \text{ km}$$

$$a - F_E = 190.5 \text{ km}$$

From the geometry of an ellipse:

$$\text{eccentricity} = \frac{\text{distance from center of ellipse to either foci}}{\text{semi-major axis}}$$

28

$$\text{or,} \quad e = \frac{a - F_E}{a}$$

$$= \frac{190.5}{7151.73}$$

For TIROS V, e $=$ 0.0266

The explanation for the second paragraph of "Orbital and Camera Characteristics":
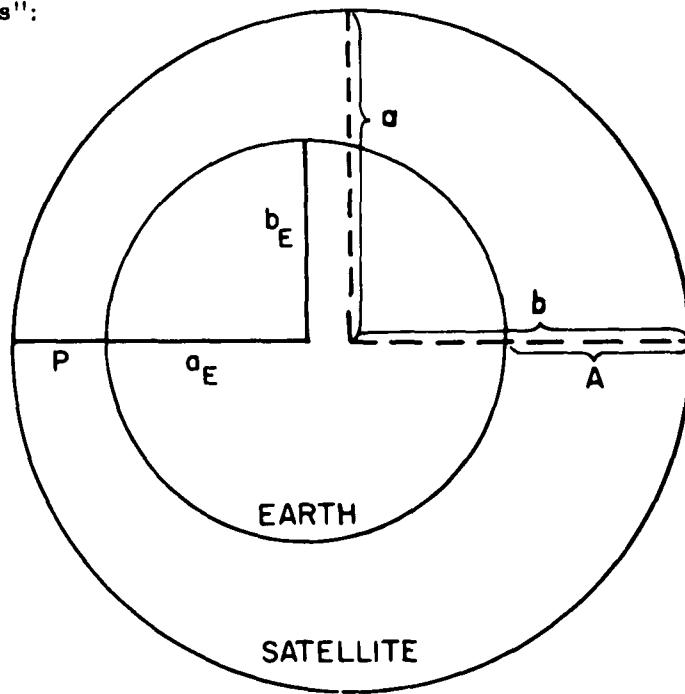
	Earth		TIROS V	
eccentricity	(e_E)	0.082	(e)	0.0266
semi-major axis	(a_E)	6378.39 km	(a)	7151.73 km
semi-minor axis	(b_E)	6356.91 km	(b)	7149.19 km
	$(a_E - b_E)$	21.48 km	(a - b)	2.54 km
			(A)	Apogee, 970 km
			(P)	Perigee, 591 km

UNCLASSIFIED

AF Cambridge Research Laboratories, Bedford, Mass. A Modification of the Fujita Method for TIROS Photograph Rectification by John F. Cronin and Leonard W. Abren, June 1963 pp. AFCRL-63-670 Unclassified Report

1. Meteorological Aids
2. Photogrammetry
I. Cronin, J. F.
II. Abren, L. W.

This paper describes a manual technique that enables the research meteorologist and others to portray with maximum accuracy a latitude-longitude net on a satellite photograph of the earth and its cloud masses.